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ENERGY
COMMISSION

Public Interest Energy Research Program
Research Development and Demonstration Plan

Attachment II - The Effects of Global Climate Change on California Water Resources

Contractor/Consultant Report

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Executive Summary

Climate change has the potential of affecting a wide variety of water resource elements. These elements include water supply, hydroelectric power, sea level rise, more intense precipitation events, water use, and a number of miscellaneous items that include water temperature changes. Some 35 items for possible research are reviewed and discussed in this chapter. After discussing these issues with other water experts, the author identified a dozen as priority items for investigation in the short-term.

In the short-term (1–3 years) this roadmap recommends addressing the objectives summarized in the table on the following page.

The Public Interest Energy Research (PIER) Climate Change Research Plan also identifies mid-term (3–10 year) and long-term (10–20 year) goals, all of which build on the short-term work listed above. This roadmap outlines a comprehensive research agenda that would be necessary to fully address the research gaps identified in this document. PIER, however, due to the limited funding, will be able to support only some of the identified areas of research. PIER is currently examining all of the roadmaps to determine which projects should be supported with PIER funding.

Objective	Projected Cost ($000)
Support the regular, consistent, and sustained measurement of hydrologically important variables	1,500*
Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data	500
Conduct a simple test of the impact on water supply of the CVP-SWP system of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume and timing.	600
Conduct detailed tests of the impact on CVP-SWP system water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume, including likely upstream reservoir operational changes	1,400
Support the development of global climate models that can better project future precipitation in California	1,000
Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage	100*
Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast	200
Measure current evapotranspiration (ET) to compare current data with earlier data	500
Assess likely changes in ET in a year 2050 or 2100 scenario with warmer average temperatures and higher carbon dioxide content of the atmosphere.	300
Conduct a systematic review and evaluation of flood protection adequacy in major multipurpose flood control reservoirs under projected climate scenarios.	600*
Model water temperatures in both regulated rivers and natural streams	400*
Support monitoring of studies and research on climate change effect on runoff in the adjoining Pacific Northwest and Colorado River regions.	200*
Total Short-term Cost	**7,300**

Note: An asterisk (*) indicates a high probability that the work can be leveraged with other ongoing efforts. The figure given is the California Energy Commission's total projected expenditure to complete each objective (over a three-year period).

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

Section 1 states the issue to be addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and how PIER plans to address those needs. *Section 3: Background* establishes the context of PIER's climate change work, as it pertains to the impact of climate change on water resources in California. *Section 4: Current Research and Research Needs* surveys current projects and identifies specific research needs that are not already being addressed by those projects. *Section 5: Goals* outlines proposed PIEREA activities that will meet those needs. *Section 6: Leveraging R&D Investments* identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. *Section 7: Areas Not Addressed by this Roadmap* identifies areas related to climate change research in this area that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being conducted to address climate change issues in this area.

Acronyms

ARB	California Air Resources Board
CAP	California Applications Program
CALFED	Cooperative State-federal program addressing water issues in California
Cal-(IT2)	California Institute for Telecommunications and Information Technology
CALSIM	A model for simulating California water resource systems
CALVIN	An economic-engineering model for water allocation
CO2	carbon dioxide
CVP-SWP	Central Valley Project - State Water Project
DOE	U.S. Department of Energy
DRI	Desert Research Institute of Nevada
DWR	California Department of Water Resources
ENSO	El Niño–Southern Oscillation
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ET	evapotranspiration
GCM	general circulation model
GHG	greenhouse gas
GPS	Global Positioning Systems
IPCC	Intergovernmental Panel on Climate Change
ITRF	International Terrestrial Reference Frame
LBNL	Lawrence Berkeley National Laboratory
mafy	million acre-feet per year
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
PDO	Pacific Decadal Oscillation
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
PMF	probable maximum flood
PRMS	Precipitation-Runoff Modeling System
TMDL	total maximum daily load
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey

1. Issue Statement

Global climate change can affect the timing, amount, and form of precipitation that California receives, as well as the level of the Pacific Ocean. Moreover, changes in weather patterns caused by climate change can affect water use and consumption. To ensure that the State's natural systems and infrastructure can accommodate hydrological changes brought about by climate change, research needs to improve detection of changes in the State's water systems and investigate the potential impacts of, and responses to, such changes.

2. Public Interest Vision

This report on suggested research on the effects of global climate change on California water resources is part of a larger effort by the California Energy Commission to analyze potential impacts on California of future global warming. The Intergovernmental Panel on Climate Change (IPCC) was jointly established in 1988 by the World Meteorological Organization and the United Nations Environment Programme to study climate change. The IPCC has issued several reports since 1990 outlining possible global warming and the effects as a result of increased amounts of carbon dioxide, methane, and other trace gases including nitrous oxide and the halocarbon gases (such as freon, which is covered under the Montreal Protocol, and the replacement hydrofluorocarbons) originating from human activities. The amount and timing of such an increase is subject to uncertainty.

The National Water Assessment Group for the U. S. Global Change Research Program (Gleick and Adams 2000) provides a good assessment of the state of research on the potential consequences of climate change on water resources in the United States, including what is known and what is not known.

The most recent IPCC Working Group I Summary Report (IPCC 2001) projects a 1990 to 2100 average global surface temperature increase of around 3°C, with a range of 1.4° to 5.8°C. The different scenarios cover a wide range of assumptions about the rate of future increases in greenhouse gases and the amount of radiative forcing in the climate system. The estimated increase in global surface temperature during the twentieth century was estimated to be about 0.6°C, much of which occurred by 1940, before the increase in man-made gases was significant (Folland and Karl 2001), and a recent significant increase after 1980 which is believed to be primarily of human origin. California inland rural temperatures do not seem to have followed the world trend and have risen only slightly since 1940 (Goodridge 2001). California coastal temperatures, even in rural locations, do show warming in the 1980s and 1990s corresponding to warmer ocean temperatures. Because of warmer temperatures, some increase in global evaporation and precipitation are projected during the twenty-first century, more likely at higher latitudes. For hydrology and water resources, precipitation is the most important variable.

Sea level is projected to rise around 0.5 meter by 2100 with a range of 0.1 to 0.9 meters (IPCC 2001). The rise during the twentieth century appears to have been around 0.2

meters, with a range of 0.1 to 0.25 meters (IPCC 1995). This estimate is consistent with the historical trend reported at the Golden Gate tide station, although it is possible that tectonic movement, or settlement, has influenced the measured stages there.

There is a general expectation that a warmer climate will lead to more intense precipitation events, thereby causing somewhat higher runoff and floods and more intense convective storms (thunderstorms), thereby affecting the rainfall statistics used for storm drainage design.

The increase in carbon dioxide, from the current 370 parts per million (ppm) to perhaps 600 to 700 ppm by the year 2100 is expected to be beneficial to plant growth, unless temperatures get too warm. To some extent, higher carbon dioxide concentrations could partly offset the higher water use (evapotranspiration) resulting from higher temperatures.

All of these projected changes, as well as some not yet identified, are likely to affect the hydrologic cycle and the water resources of California.

3. Background

3.1 Water Resources in California

Northern and central California precipitation is quite seasonal, typical of a Mediterranean climate, with cool wet winters and warm dry summers. On average, half the annual precipitation occurs in the three months of December, January, and February. Three-fourths occurs in the five-month November through March period (see Figure 1). The only significant departures are in the dry southeastern desert areas, which have a summer monsoon peak as well as a winter season maximum.

In California, the wetter regions contributing most of the State's runoff are in the north. Most of the demand for water is in the central and southern portion of the State. Three-fourths of the State's 87 cubic kilometers (71 million acre-feet) of average natural runoff originates north of Sacramento, the State capital; about 80% of the demand for urban and agricultural water is south of Sacramento. Approximately 3.6 million hectares (9 million acres) of farmland are irrigated, producing about 13% of the agricultural value for the entire United States (DF&A 2000). Irrigated acreage is expected to decline slightly, perhaps 5%, by year 2020 as population increases from 34 million in 2000, to a projected 48 million. In recent decades, environmental needs are receiving increasing attention. Demands for more fresh water for fisheries and wetlands are rising, partly at the expense of agriculture. Water conservation and other water management measures can help stretch supplies (on the order of 3 to 5%) but these tools cannot solve major shortfalls.

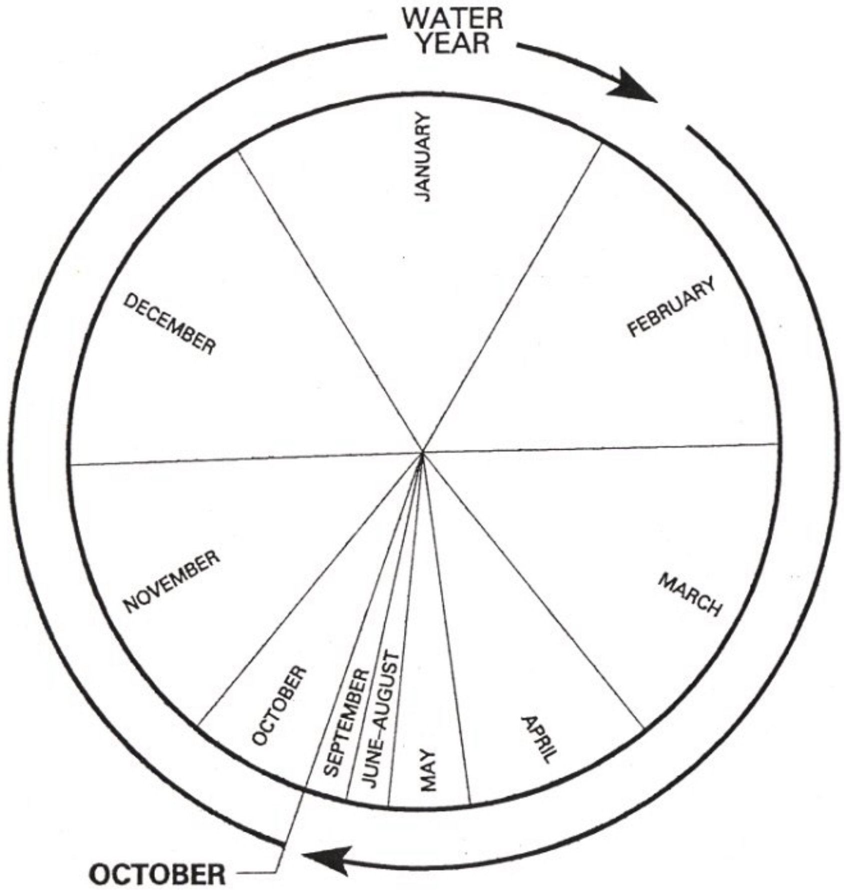

Figure 1. Monthly Precipitation Distribution in the Sierra Nevada
Source: 1947–1986 precipitation records for Sierra stations as compiled by DWR and Scripps Institution of Oceanography.

Water development in California is based on the concept of storing water during the wet season and in wet years with long-distance conveyance to areas of need. Major water transfer projects have been built to convey water from areas of plenty to the drier central and southern portions of the state. The tidewater region of the Sacramento-San Joaquin Delta is the hub of major water transfer; water quality there can be affected by salinity intrusion from the ocean via San Francisco Bay.

Large reservoirs in the north provide water storage and flood control. Water is then released downstream to be exported by large pumps in the southwestern corner of the Delta. During low-flow months, additional water is released to repel ocean salinity incursion in the western Delta as a hydraulic barrier to preserve suitable fresh water quality within the estuary and for export. Total export pumping averages around 7.5 cubic kilometers per year (6 million acre-feet). These exports supply approximately one-fourth of all the current water use in central and southern California including the San Francisco

Bay area. The rest of the use is supplied from local surface and groundwater sources and from the Colorado River.

The large reservoirs are multi-purpose projects built to provide flood control during the winter wet season. Figure 2 shows an example of flood control operations for Lake Oroville, based on California Department of Water Resources (DWR) operations records. The upper and lower lines are flood space requirements, less when the watershed is relatively dry and more when wet (lower line), and show how the permissible storage changes during a season. The large storm in mid-January caused a rapid change in basin wetness and allowable storage. Excess runoff was temporarily stored during the winter storm (note the sharp rise in reservoir storage in mid-January), then released after the storm. A substantial amount of winter precipitation has historically been stored in the snowpack. During the spring (late March, April, and May), flood control requirements are eased and, if all goes well, the reservoirs fill from spring snowmelt (see Figure 2). In this example, reservoir storage peaked in early June, but did not quite fill before the higher summer water demands started the seasonal draw down cycle. Potential loss of a large fraction of snowmelt runoff would make it more difficult to fill the large reservoirs in most years, with corresponding reductions in water supply yield, some losses for recreation and hydroelectric power, and possible temperature problems for downstream fisheries.

Based upon Department of Water Resources Bulletin 160-98 (DWR 1998), estimated applied water use and supply are shown in Table 1, in million acre-feet per year (mafy), at the 1995 level of development. Current uses in 2001 are believed to be about the same as those in the table. The urban category includes water for commercial, industrial, residential, and government uses, including many city parks.

Table 1. California 1995 Water Budget with Existing Facilities and Programs (mafy)

	Average Year	Drought Year
Water Use		
Urban	8.8	9.0
Agricultural	33.8	34.5
Environmental	36.9	21.2
Total	**79.5**	**64.7**
Supplies		
Surface Water	65.1	43.5
Groundwater	12.5	15.8
Recycled and Desalted	.3	.3
Total	**77.9**	**59.6**
Shortage	**1.6**	**5.1**

Source: DWR Bulletin 160-98.

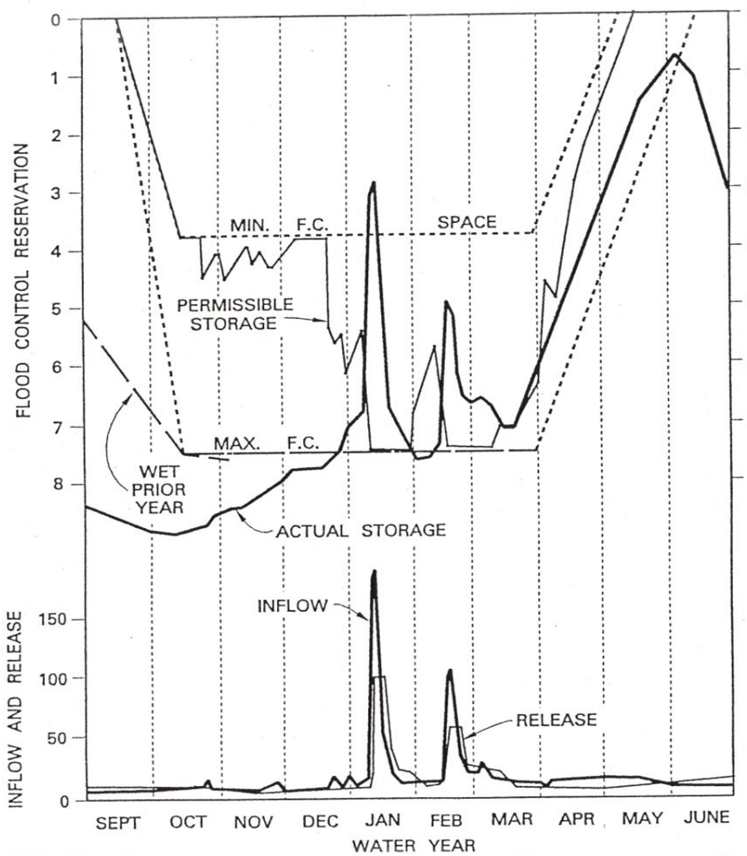

Figure 2. Typical Example, Reservoir Flood Control Operation
Source: DWR Lake Oroville operating records for Water Year 1980.

The shortage includes groundwater overdraft of about 1.5 mafy, mostly in the San Joaquin Valley. Instream wild and scenic river flows account for 23.6 and 10.6 million acre-feet (maf), respectively, of the estimated environmental use in average and drought years. (The primary reason for the drop-off of environmental usage in a drought year is that this category includes the North Coast wild and scenic river runoff, which is much lower in a dry year.) Of the total out-of-stream usage for urban and agricultural purposes, nearly 80% was used by agriculture. Updated figures will be available in about a year in DWR's Bulletin 160-2003, but the ones above are believed quite representative of today's conditions.

Climate change could affect both water supply and water demand. Unless water supply becomes deficient, which will cause yield losses, water use will probably only show a small increase in evapotranspiration. A rise in cool season temperatures may enable more double cropping of annual or seasonal crops. Currently irrigated land in the State totals about 9.1 million acres, with about 0.4 million acres of multiple crop, for a total crop area of 9.5 million acres (DWR 1998). For some perennial crops, such as alfalfa, a longer growing season could generate more cuttings, hence higher production per acre, but with a proportional increase in water use per acre. A rise of 3°C could trigger crop shifts from the more southern valleys to the north.

The more substantive changes to be expected are in the water supply sector. Higher snow levels during winter storms mean more direct runoff from rain, less snowpack, and less spring snowmelt runoff. The shift in runoff patterns from spring snowmelt into winter runoff as a result of temperature increases would cause major changes in usable water (water available at the time of need) from major California rivers and reservoirs, especially in the lower elevation northern Sierra Nevada. The following chart from data in DWR files and operation studies, may help illustrate this point.

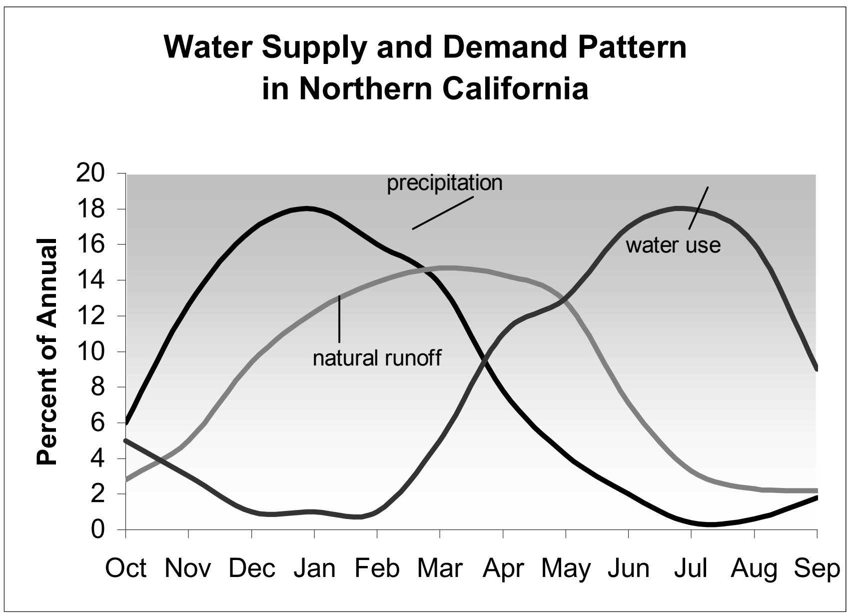

Figure 3. Water Supply and Demand Patterns in Northern California
Source: DWR.

The first curve (precipitation) shows the average monthly pattern of precipitation in the northern Sierra. The peak precipitation month is January; December and February are not far behind. These three months account for half the annual precipitation. (The water year in Figure 3 begins in October and ends in September to correspond to the normal runoff season.) Rainfall patterns are quite similar in all of northern and central California. The second line (middle curve) shows runoff in the Sacramento River basin. The primary reason for the lag is the natural storage of a portion of the winter precipitation as snowpack and its gradual release during the spring melting season. The summer peaking line is a typical demand for water use in northern and central California. Snowmelt runoff provides a substantial share of early demand directly; as demand rises and natural runoff decreases, stored water must be used to make up the difference. As a general rule, less spring runoff means a greater need for winter storage to provide the same annual demand. For California's major foothill reservoirs, added winter runoff often is not storable because of the need to maintain flood control space at that time.

In addition to seasonal patterns, variability in annual runoff is an important element in California water supply. Dry years are interspersed with wet years. The records of precipitation and runoff show that extremely dry periods often last several years. Figure 4 shows the history of Sacramento River system unimpaired runoff (sometimes called the Four River Index). The bars are coded in the five categories, from wet to critical, used in determining Delta water quality criteria (the 40-30-30 Index). The driest single water year was 1977 at about 28% of average and the wettest was only six years later in 1983, at 207% of average. The driest two-year period was 1976 and 1977, at about 36%. Two six-year sequences of drought stand out: 1929–1934 and 1987–1992. Many reservoirs were built to maintain a certain level of planned deliveries or reliability, should there be a repeat of the 1929–1934 drought.

One of the concerns in a changed global climate is whether droughts would be either longer or more severe. Some additional data on the range of variations in historical climate, and presumably some insight on likely future variations, can be gleaned from paleoclimate reconstructions, including tree ring studies.

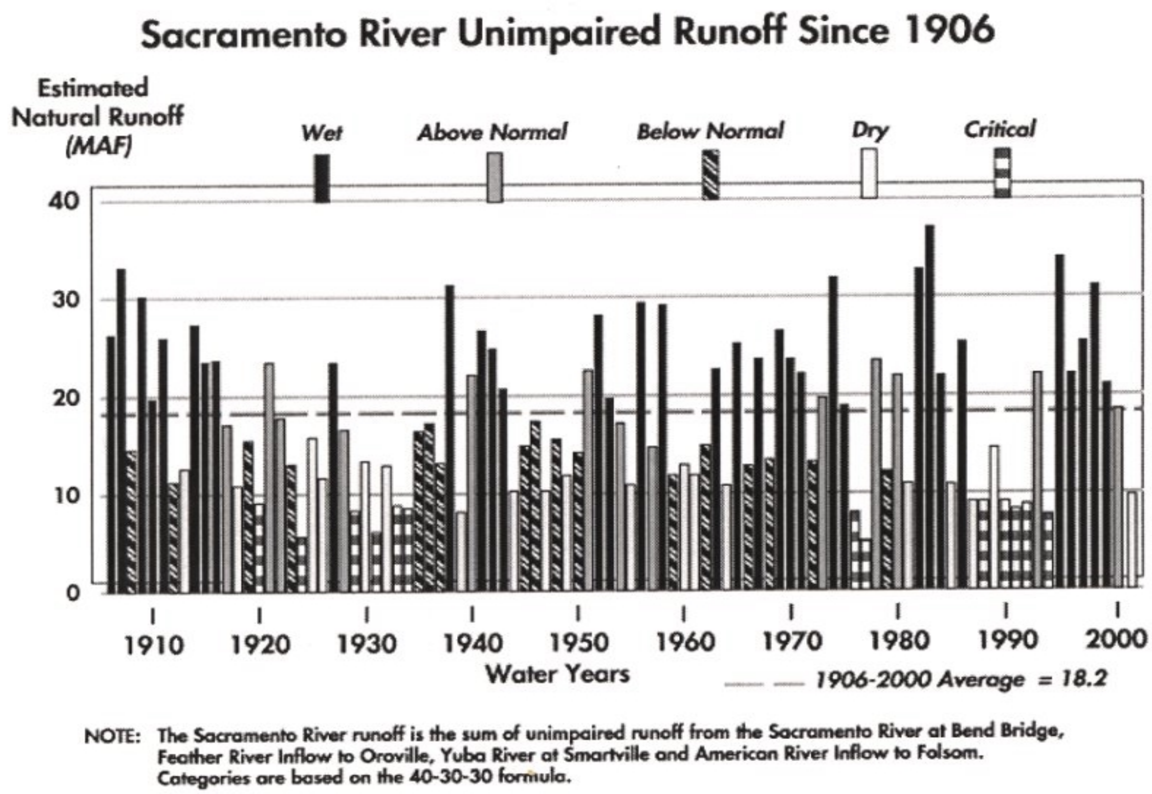

Figure 4. Sacramento River Unimpaired Runoff Since 1906
Source: DWR Snow Surveys Program records.

Assuming no significant change in average precipitation, less spring snowmelt runoff would make it more difficult to refill reservoir flood control space during the late spring and early summer of many years, thus reducing the amount deliverable. Lower early summer reservoir levels also would adversely affect recreation and hydroelectric power. If precipitation increases sufficiently, it is possible for snowmelt runoff to increase in the higher elevation southern Sierra watersheds (Dettinger 2000). Each of these issues is worthy of further analysis and research.

Warmer temperatures are likely to lead to more extreme storm events. If anything, this would require that all currently available winter flood storage space in the reservoirs be kept open, or would require more space.

Sea level rise could especially affect the Sacramento San Joaquin River Delta, the hub of California's water transfer system. Higher tide levels would pose additional problems to the precarious Delta levee systems, with a risk of more island inundations and the corresponding threat to export water quality.

3.2 The PIER Focus

Although the specific effects of climate change on California's water resources are still uncertain, research to date indicates that shifts in precipitation and sea level rise will be issues that must be addressed in the near-term future. To ensure the reliable delivery of water, the protection of the State's infrastructure, and the safety of its citizens and their property, California must have the tools and methods in place to be able to collect and analyze hydrology data throughout the State. Further, to ensure a rapid and informed response (and to leverage state resources), this data must be readily accessible to researchers in a wide variety of disciplines.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Examining the impacts of climate change on the State's water resources and potential responses to those changes is one such issue. PIEREA aims to address this topic through its own targeted research and to attract collaborators that will share data and work with PIEREA.

Other PIEREA roadmap chapters address other ecological, technical, and economic aspects of climate change effects on water resources in California. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

There are several areas of potentially fruitful research on the impacts of climate change on California's water resources. These can be grouped into items affecting water supply, hydroelectric power, sea level rise, water use—especially in agriculture, flood risk and storm drainage design, and other categories such as river temperature and water quality (primarily mineral content and dissolved oxygen). One needs to have a good understanding of potential physical changes in order to focus research priorities. Because it is uncertain which physical changes to expect, this is no easy task. Monitoring, both to detect changes and to calibrate atmospheric and hydrologic models, is basic to successful research.

The following discussions outline the status of current work in these areas and identify areas affecting water resources where new or additional research is needed. Table 2 attempts to give a roadmap overview of research suggestions.

Table 2. Roadmap on Water Resources Research Suggestions

Major Task	Subtasks
Monitoring	• Weather changes • Hydrologic changes
Water Supply	• Modeling future precipitation • Snow level and runoff changes • Test operation of CVP-SWP system • Impact on reservoir recreation • Winter flood control space • Groundwater recharge • Offstream storage • Changes in radiation • Climate change in adjacent regions • More understanding of hydrologic variability
Loss of Hydro at Foothill Reservoirs	• Average conditions • Long base period studies
Sea Level Rise	• Catalog trends along coast • Evaluate Golden Gate tide datum • Effect on Delta levee stability • Salinity intrusion • Silt in the Delta • Vulnerability of coastal Marshes • Coastal aquifer salinity intrusion • Grade line of sewers and storm drains • Coastal erosion
More Intense Precipitation	• Risk of bigger floods and rain events • Revise depth-duration-frequency data • Bigger probable maximum floods • Erosion potential
Water Use	• Changes in ET and crop water use • Recent changes in ET • Change in growing season • Effect of changed ET on aquifer recharge • Increased smog effect
Other Items	• Water temperature • Transition zone erosion • Water weeds • Wild fires • Increased salinity • Drinking water treatment

4.1 Monitoring

Regular, consistent, and sustained measurement of hydrologically important variables are essential to track what is happening and to verify model predictions. This means continuing measurements of variables such as precipitation and other climate data, streamflow, snowpack, and ocean and Delta tide levels.

The National Weather Service, in its newly reorganized Climate Services Division, is developing a climate reference network of 250 weather stations as a national benchmark of long-term climate monitoring stations. These would be stations with a long history (50 years or more) which are expected to have a stable local environment, not subject to urbanization or other changes, during the next 50 years (Robert Livezey 2001, personal comm.). About five stations will probably be located in California. They are likely to be lowland stations, because good mountain stations are difficult to sustain, especially where snow is part of the precipitation mix. Consideration should be given to establishing and maintaining station networks along gradients such as east to west, north to south, and across climate zones. In view of the outlook for substantial changes in snowpack, the measurements in the high Sierra snow zone should be increased, including some discrete new sites in wilderness areas. Leaving out the wilderness leaves large holes in data coverage in an area likely to change. High elevation climate trends and variations are not as well understood as those at lower elevations, yet do affect vital elements of the State's economic structure.

A useful start on high-elevation monitoring has begun in Yosemite National Park. As part of the University of California's California Applications Program (CAP), the Climate Research Division of Scripps Institution of Oceanography installed a number of snow measurement and meteorological instruments in the park. Their purpose is to monitor meteorological, snowpack and hydrologic conditions in more detail and with greater consistency than in the past. This project is supported by the National Park Service (NPS), National Oceanic and Atmospheric Administration (NOAA), California DWR, Desert Research Institute of Nevada, as well as the Cal-(IT^2) program and the National Science Foundation (NSF). Besides its use in monitoring climate change, better information in the snow zone may help improve water supply runoff forecasts and flood forecasts.

Research Needs

Basic data programs are relatively expensive and, like maintenance, are subject to budget cuts in tough financial times. Recognition of their foundational value is something to be stressed when dealing with funding agencies. Continuing assessment of changes in runoff patterns, sea level, precipitation events, and water use are important elements.

4.2 Water Supply

Providing an adequate supply of developed water for all California uses is already a problem, especially during dry years. The key variable is the amount of precipitation in the form of rain and snow on watersheds and the resulting runoff. Projections of regional precipitation, however, are not reliably available from global climate models and it is doubtful that definitive projections will be forthcoming soon. Dry years and dry periods are of most interest to water supply planners, although flood events are also a concern.

The problem of reliably projecting precipitation will be the subject of continuing investigations by PIER-sponsored work on regional modeling, by climate researchers at Scripps, at Livermore and Berkeley National Labs, and by general circulation model

(GCM) modelers themselves. The national assessment on water (Gleick and Adams 2000) and the hydrology study by Miller et al. (2001) that is part of the current Energy Commission/EPRI project on Climate Change Impacts on California have looked at some of the model extreme precipitation and flooding cases to see what they reveal. Both the Hadley and the Canadian GCM, and the National Center for Atmospheric Research PCM model, suggest more frequent and more severe flooding in California (Gleick and Adams 2000, Miller et al. 2001).

Higher temperatures could have a large impact on natural runoff, especially in the lower elevation northern Sierra. Assuming that other factors (such as precipitation) will be the same, higher snow levels during winter storms mean more direct rain runoff, less snowpack, and less spring snowmelt runoff.

In the semi-arid climate of California, effects of climate change on water supply are paramount. As noted before, the hydrologic parameter of most importance is precipitation in enough detail to analyze individual river basins. So far, results of GCMs have not been consistent, either as a 100-year preview snapshot with higher greenhouse gases or as a progressive 100 future years of varying seasons.

The best approach for initial work on hydrologic changes would be to assume about the same precipitation and precipitation patterns as now, but with warmer temperatures. However, it would also be a good idea to look at some of the extreme model precipitation cases in the National Assessment and, as is being done, in the current Energy Commission/EPRI project on Climate Change Impacts on California.

4.2.1 Modeling Future Precipitation

Future precipitation is probably the most important variable influencing water resources and water supply. It is also most difficult to predict at the regional and watershed levels. It should be no surprise that research should continue into modeling likely future precipitation in enough detail in time and space to feed into individual watershed runoff models. Good work has been done in the University of California system, including Scripps and the Lawrence Berkeley National Laboratory, on using GCM models developed by other institutions and downscaling data into regional climate models. Continued, but slow, improvement in such models is expected.

Lawrence Livermore and Lawrence Berkeley National Laboratories—in collaboration with the National Center for Atmospheric Research (NCAR) in Boulder and other groups—are working on a Community Climate System Model. This model's planned scale, at an approximately 100-kilometer spacing grid, should improve GCM projections considerably in the next five years. Finer grid spacing will be needed, however, to better simulate mountain area precipitation.

Research Needs

Climate modelers should continue to verify and improve the large GCMs and their handling of precipitation. Newer, more powerful computers will help, and continued improvement is expected, but it is doubtful precipitation on the scale needed by the hydrologist can be modeled well in the near future. There are so many variables in modeling the atmosphere that it may not be practical to expect reliable precipitation simulation to be provided at the watershed scale in the next decade. However, atmospheric modeling should be a continuing effort and the uncertainty of future precipitation and precipitation patterns is in itself a topic of future research. There is some consistency in modeling results thus far to show a tendency for the southern part of California to be drier and the north to be wetter (Larry Gates 2001, personal comm.).

It is essential that knowledgeable university groups continue to monitor progress of the various GCM model centers around the world. This would include NCAR, the British Hadley Centre, the Canadian Centre, and the Geophysical Fluid Dynamics Laboratory at Princeton. Special attention should be given to the Community Climate System Model work previously mentioned. For now, since there is more confidence in temperature projections, the more robust temperature results can be used in watershed models, assuming the current patterns and amounts of precipitation continue in California. At the same time it would be a good idea to look at some of the more extreme cases, wet or dry, to see what the effect would be.

4.2.2 Snow Level Changes and Resulting Runoff Changes

Existing models are capable of modeling snow level and runoff changes. The U.S. Geological Survey-developed detailed hydrographic unit model, Precipitation-Runoff Modeling System (PRMS) (Leavesley et al. 1983), has been used to model a number of California basins. The National Weather Service flood forecasting model (National Weather Service River Forecast System, or NWSRFS) (Page 1996) may be useful as an alternative for evaluating some scenarios. This system was the major tool used by Lettenmaier and Gan in their seminal study of the sensitivity of the Sacramento-San Joaquin River basin to global warming (Lettenmaier and Gan 1990).

Some guidance can be expected in the near future by downscaling GCM precipitation and temperature and inputting that into hydrologic models for each watershed, as is being done by Dr. Norman Miller and his associates at LBNL. Their hydrologic model, which is really the NWSRFS model, may also have potential in deriving unimpaired runoff of major rivers for ultimate climate scenarios as input to reservoir operation studies by DWR and others.

Research Needs

Projected changes in natural runoff from California's major water production rivers should be evaluated, initially assuming precipitation patterns like the present but with higher snowpack elevations. These rivers would predominately be the major ones draining the southern Cascade and Sierra Nevada region. Ideally it would be nice to have a watershed model and input simulating the entire watershed, including its vegetation, in all future climate regimes, but that is for the longer-range future. Practically, running a basin simulation with historical precipitation with seasonal temperature changes from the GCM work seems like a reasonable approach, using the PRMS and/or NWSRFS watershed models. Modified runoff by month, which could be obtained from the preceding watershed models, could then be routed through the reservoir systems downstream to estimate the change in the usable water supply yield.

4.2.3 Test Operation of CVP-SWP System

The combined Central Valley Project and State Water Project (CVP-SWP) system furnishes about 30% of the State's net demand for urban and agricultural water. The reservoirs of these two projects are, in large measure, located on watersheds (Trinity, Sacramento, Feather, and American) likely to see large shifts in runoff patterns as a result of rising snow levels. At least 50 years of hydrology are suggested as a minimum length for comparisons. Currently, many studies are made for the 1922–1994 historical period of 72 years and the model hydrology is now being extended through water year 1998 for a 77-year period. The longer period includes simulated operation during the two major 6-year historical droughts, 1929–1934 and 1987–1992.

Research Needs

Existing monthly reservoir operation models, like DWR's CALSIM II model, should be used to run some simple (and later, more detailed) two-step tests of the impact on water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume. The CALSIM monthly simulation model, or something like it, is the best model to show potential impacts on water supply. CALSIM II simulates operation of the State Water Project and Central Valley Project system facilities, including the Sacramento and San Joaquin River system, Delta operations, and SWP and CVP deliveries to northern, central, and southern California.

These test evaluations should logically proceed in two stages, (1) a simplified run involving approximate adjustments to major project reservoir monthly inflow and (2) more detailed studies involving all major facilities, including local reservoirs and upstream power reservoirs.

Initial studies (in the two-year time frame) should focus on the assumption of precipitation similar to the historical amounts, except with higher temperatures. The initial crude estimate, which may also be confirmed with the CALVIN model developed at U.C. Davis, should provide guidance to ongoing DWR Bulletin 160 water planning and the CALFED process. The simple test, which could be done in a year by DWR, would enable some initial planning responses; better and more detailed operation studies with all major facilities in the Central Valley watershed could follow. Adjusting the operation of other locally operated reservoirs (including upstream power reservoirs) could require studies on how to approximate such an effect for initial runs. A compatible estimate of changes in salinity repulsion requirements in the Delta, during those months when water quality standards control Delta operations, would be part of the CALSIM runs. Outputs would compare combined water project export supply, foothill reservoir hydroelectric power production, and flood control releases.

In the three- to five-year time frame, several runs could be made with varying wet and dry GCM scenarios, hopefully with year-by-year results over a long hydrologic base period, to fully evaluate the hydrologic impact of potential climate change. These later studies might include some alternative reservoir operation strategies.

Watershed input (unimpaired or natural flow of major streams) for the more detailed CALSIM model runs could be obtained from further development of the PRMS models being worked on by Scripps Institution of Oceanography. Basic input to the PRMS models would be from several GCM runs. An alternative may be the wetlands and watershed models used in the current EPRI/Energy Commission study being conducted by LBNL's California Water Resources Research and Applications Center, headed by Dr. Norman Miller. The PRMS models seem to be able to handle the snow zone changes. The NWSRFS model used by LBNL is probably better at assessing flood changes, and may be improved when Dr. Miller's group completes subdividing the incorporated Anderson snow model into finer zones or levels.

4.2.4 Impact on Reservoir Recreation

Lower summer water levels in foothill reservoirs have a strong economic impact on reservoir recreation. Lake fishing and boating are prime pursuits of recreationists; reduced volume and area has a negative influence on the fishery, too. Many of the nearby foothill communities depend on reservoir recreation and visitor spending as a substantial component on the local economy. For example, low reservoir levels at Lake Oroville during the summer of dry year 2001 noticeably hurt the local economy, according to local newspaper accounts. According to figures from the Department of Parks and Recreation, visitation at the Lime Saddle recreation area on Lake Oroville during May through August decreased about 35% in the low water years of 2000 and 2001.

Warmer summer weather may drive some visitors to higher elevation lakes, but it may also lengthen the recreation season because of presumably warmer spring and fall temperatures. Reservoir recreation is one of the many economic impacts likely as a result of global warming in California.

Research Needs

The CVP-SWP system water yield analysis, which can include monthly reservoir storage, would be a base upon which to evaluate recreational impacts, at least initially. Because a 3°C rise by year 2100 is likely to be a long-range assumption, smaller rises could be estimated by proportioning results downward for nearer futures or for smaller temperature-increase assumptions. It would be nice to get some sense of effects for a range of temperature increases from 1 to 5°C.

4.2.5 Winter Flood Control Space

Some increase in the size of large winter floods is likely, according to the IPCC (Working Group I Summary Report 2001) and the National Assessment (Gleick and Adams 2000). Most flood control reservoirs are multipurpose, with a certain amount of dedicated flood space in the wet season, originally designed to protect downstream areas from a very large flood. That space may not be adequate if future floods are larger, but an increase in reservoir flood space would reduce all other functions of the reservoir, primarily affecting water supply and power. The alternative of increasing downstream channel capacity in developed areas will be difficult and costly. However, there may be some areas where levee setbacks are feasible. There may also be some situations where increasing the flood plain for moderate floods could add to groundwater recharge

Konstantine and Aris Georgakakos and their associates (Carpenter and Georgakakos 2001, Yao and Georgakakos 2001) have been looking into methods of improving reservoir flood control and power operations at Folsom reservoir with probabilistic forecasting. Their method is to make ensemble forecasts[1] of inflow and develop operational strategies to try to optimize benefits. The U.S. Bureau of Reclamation in Sacramento is testing use of probability inflow ensembles now, with guidelines on reservoir flood operation for Folsom from a model developed by Dr. David Bowles of Utah State University in Logan.

Another modeling option for Central Valley flood runoff and foothill reservoir operation is the hydrology and hydraulics models being developed for the Corps of Engineers Comprehensive Study of the Sacramento and San Joaquin River basins. These models can simulate flows throughout the river systems that flow into the Delta (the models do not extend into the Delta waterway system). The model work is nearing completion; with some adjustments, these models should be able to handle watershed meteorological data generated by GCMs. The models are in use for flood studies in the Sacramento District office of the Corps.[2] The upstream watershed hydrology portion is being developed by the Hydrologic Engineering Center in Davis.

Currently, the months of greatest risk of a large flood occurring are December, January, and February, and this is reflected in the seasonal shape of the flood reservation envelope (See Figure 2.) However, it is unclear whether the late winter and spring risk is increased or decreased in a warmer world. If some encroachment in midwinter reservoir flood space could start earlier in the spring, this could reduce some of the loss in water supply and hydroelectric power resulting from snow level and runoff pattern changes.

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[1] An ensemble forecast is a series of equally likely future inflows (for example 10 runoff scenarios) for given conditions, reflecting the uncertainty of weather forecasts.
[2] For more information, contact the comprehensive study staff.

Research Needs

Researchers should conduct a systematic analysis of the likely increased need for flood control due to climate change. It is important to evaluate whether or not California's reservoir space is adequate if future floods are larger, and examine how an increase in reservoir flood space would affect all other functions of the reservoir (primarily water supply and power). In addition, research should explore the feasibility and cost-effectiveness of levee setbacks, new compensated flood plain storage, and alternatives for increasing downstream channel capacity in developed areas.

A small but useful project would be for PIER or the Energy Commission to sponsor a two-day seminar in Sacramento, at which the operations research specialists would explain in detail their research and suggested operational changes. The target audience would be those who operate, regulate, or plan flood control operations for major Central Valley foothill reservoirs.

Currently, the U.S. Corps of Engineers and the State Reclamation Board are engaged in a comprehensive study to improve flood management in the Sacramento and San Joaquin Valleys. Information on possible changes in flood runoff—both rain floods and, for the southern Sierra, snowmelt floods—would be valuable to them as they seek to develop alternatives for an admittedly inadequate flood system.

Research in this area also needs to target the change in risk of a large flood during each month of the rainy season—particularly whether the late winter and spring risk is increased or decreased in a warmer world. A careful examination by knowledgeable scientists of historical intense rainfall patterns and those projected by the GCMs could provide some new information. There may be one set of figures to maintain the flood protection in the original formulation, another set for the 1-in-100 year flood, and perhaps a third for the 1-in-200 year flood. In many cases, the feasibility of adding more flood space in existing reservoirs is doubtful, but the analysis would highlight the potential deficiencies in a modified climate. In some cases, there may be possible exchanges of water supply space with that in groundwater basins or new surface storage.

4.2.6 Groundwater Recharge

Natural groundwater recharge comes from streambed percolation and deep percolation of precipitation in excess of rooting zone moisture storage and the evapotranspiration of vegetation. In addition, in many basins, there is also deliberate recharge by spreading basins (artificial ponds to percolate water), delivery of water into natural watercourses for seepage and percolation, and deep percolation beyond the rooting zone on irrigated land. Even with higher CO_2 concentrations, a different (warmer) climate would likely increase the ET usage of vegetation with less left over for deep percolation. This issue is discussed in more detail in the water use section. If stream runoff becomes more flashy, that too reduces the time period for streambed seepage and percolation. Again, recharge amounts would be strongly influenced by precipitation. If essentially historical precipitation continues, the net result probably would be a loss in the amounts historically recharged. Randall Hansen, with the U.S. Geological Survey (USGS) San Diego District office, has been studying the Santa Clara–Calleguas Basin of Ventura County, comparing historical response and some climate and long-range forecast responses. His work, which is continuing, could be a useful springboard for further research.

Research Needs

Studies of several typical groundwater basins in California should be undertaken to see how sensitive groundwater supply is to climate change. This could include some of the wetter and drier GCM scenarios. Research should focus on investigating the amounts of return flow and deep percolation of agricultural and urban applied water, and how these amounts might change in a different climate.

4.2.7 Offstream Storage

Potential impacts on offstream reservoir storage are similar to groundwater supply in many respects. The difficulty of winning approval of reservoir sites on rivers has caused water planners to turn to offstream sites, selecting a dry valley to fill with water diverted from a major river. Because of the physical limitations of conveyance systems (pumps, canals, or pipelines) bringing water from a river to the offstream reservoir, the amount of water capturable is less than it would be with a dam and reservoir on the stream. An increase in flashiness of stream runoff would reduce usable supply. This can be offset by larger diversion facilities, but at a cost. On the other hand, a wetter scenario could increase usable diversion supplies.

On snowmelt streams, the effect would probably be compounded, because snowmelt runoff is much less variable. Snowmelt runoff tends to rise relatively slowly, fluctuate, and then recede slowly. Conversion of a portion of snowmelt into winter rain runoff would yield a more variable flow, with potentially less water available between storms.

An analysis of proposed CALFED offstream storage sites is suggested, to see how much variation there is likely to be in runoff of source streams when flows are modified for global warming.

The author is not aware of any current work on this item of study.

Research Needs

An analysis of proposed new CALFED offstream storage sites is suggested to see how much variation there is likely to be in runoff of source streams when flows are modified for global warming.

4.2.8 Changes in Radiation

Greater concentrations of greenhouse gases may change incoming or reflected radiation enough to make a difference in snowpack melt. In the spring, it has been estimated that around 80% of the energy for melting snow comes from radiation. Incoming solar radiation is in the short wavelengths; reemitted radiation from the atmosphere is in the longer, infrared wavelengths. Higher concentrations of greenhouse gases, especially water vapor, could increase the infrared radiation reflected back from the atmosphere. Absolute humidity is expected to rise in a warmer world.

The University of California at Santa Barbara has conducted work measuring the effect of solar radiation input on the snowpack at a remote site in Emerald Lake basin in Sequoia National Park, but net solar radiation input to the snowpack is difficult to measure accurately in the field because of reflections from many surfaces.

Research Needs

It is recommended that careful experiments measuring radiation and its effect on snowmelt be conducted in the high Sierra snow zone. There should be enough difference between low humidity and high humidity days to see if this factor is significant. This work could build on the information developed by U.C. Santa Barbara. A more accessible site is recommended, perhaps along Highway 120 in Yosemite Park. Scripps has begun research studies in Yosemite National Park.

4.2.9 Effect of Climate Change in Other Regions

The Colorado River, which drains a huge area of the American Southwest, is a very important component of California water supply, especially in the south. Earlier studies (Nash and Gleick 1993) have indicated a high probability of change toward less runoff. Since the Colorado River water supply is already fully subscribed, if not oversubscribed, a reduction in average runoff could affect California's water supply, as well as that of the other Colorado River Basin states. In addition, hydroelectric power could be affected, especially by generation at Glen Canyon and Hoover dams, due to changes in reservoir levels.

California's long-term entitlements to Colorado River water are 4.4 million acre-feet. In recent years, California's net diversions have been around 5.2 million acre-feet, and the State is being forced to reduce its take as demands in other states build toward use of their full entitlements. Climate change in the watershed could exacerbate the water supply situation. It is also possible that a wetter scenario could improve Colorado River runoff, even to the point of generating more flood problems on the lower river.

California depends on the Pacific Northwest, including the Columbia River system, for about 10% of its electric energy supply. As seen during 2001, when Colombia River runoff is down, there is an impact on California's electric power supply and reliability.

In conclusion, the effects of climate change, especially precipitation, in the adjoining Pacific Northwest and the Colorado River watershed would have an impact on California—on electricity supply for both regions and on water supply for the Colorado River region.

Research Needs
As noted above, California may be affected by changes in annual runoff in the Pacific Northwest and Colorado River regions. It is anticipated that interested regional parties will begin new research and studies in these regions. It is recommended that the California Energy Commission and the California Department of Water Resources monitor results of these studies as they are completed and try to assess what they might mean for California water supply and electric energy imports.

4.2.10 Better Understanding of Hydrologic Variability

California climate is a sequence of wet and dry years. It would be useful to determine what climate influences, such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), are linked to drought and floods in California. The dynamics of extreme events—whether flood or drought—are not well understood, and there are questions about how well these are simulated in atmospheric models. There may be merit in extending the observed climatic record of variation by extracting high-resolution paleoclimatic data from physical indicators such as tree rings and lake sediment—especially when looking at driving forces for persistent, severe droughts. Any predictive skills that could be developed would be useful to water managers.

To the extent information can be developed on climate relationships to floods and droughts, the atmospheric GCMs should be tested to see how well these links are reproduced.

Research Needs
Researchers should make a systematic effort to look at past droughts and flood events, to categorize how they are linked to broader regional and worldwide weather patterns and to identify how they develop. There are likely to be multiple links and influences. These studies can build on research over the years by Scripps Institution of Oceanography, the Laboratory of Tree-Ring Research at the University of Arizona (in regard to past patterns determined from tree ring studies), and the National Weather Service (NWS) Climate Analysis Center.

4.3 Loss of Hydro at Foothill Reservoirs

There are essentially three elements of California hydroelectric power production: (1) run-of-the-river power plants taking advantage of unregulated or incidentally regulated river flow, (2) systems where flow is regulated by upstream power storage reservoirs where flood control is not a requirement, and (3) foothill reservoirs where power is produced more as a by-product of reservoir operations for water supply and flood control. It is difficult to say what impact climate change would have on the first group. There may be more usable water flow; on the other hand, loss of snowmelt with its more even hydrograph (i.e., pattern of flow) may reduce hours of suitable flow. The effect on the second group of plants, where flow is regulated by upstream power reservoirs, is likely to be small. Earlier snowmelt and some winter runoff would fill the reservoirs sooner, but the operators could hold the water until the summer high electrical load season and probably produce about the same power (assuming no significant changes in annual precipitation).

The foothill groups of major multipurpose reservoirs would be expected to see the major effects. Some preliminary studies (Roos 1990) at Oroville indicated a summer season energy loss of 3 to 7 %, depending on whether operators tried to provide the same water service or reduce water releases to keep operating heads higher. The basic problem is the difficulty in filling the reservoir because of reduced snowmelt runoff after winter season flood control limits are relaxed in the late spring. Because water supply is a primary purpose of all the foothill reservoirs, an analysis of the power impact at each of the twelve major multipurpose projects could be conducted. A survey of the effect on power production for average conditions should not be very complex. The impacts probably will vary greatly from one year to another, depending on the pattern and amount of runoff. It is possible, with a wetter future climate scenario, to get an increase in hydroelectric energy production (Yao and Georgakakos 2001).

Dr. Lund at U.C. Davis is currently adapting the economic-engineering CALVIN model for power at several CVP- SWP reservoirs; some results are expected later in 2002.

To the author's knowledge, no systematic study has been made on the potential effect on hydroelectric power in California due to global warming.

Research Needs

Researchers should conduct an analysis that includes the modified monthly inflow over at least a 50-year span of hydrologic years, to better evaluate the changes in wet and dry years. Results from snow level and corresponding runoff changes and modified demands from CVP-SWP system operation are probably necessary to obtain reliable results.

4.4 Sea Level Rise

The IPCC has projected that sea level will rise between 0.1 to 0.9 meters by year 2100 (IPCC 2001). The median projection would be 0.4 to 0.5 meters—or about 1.5 feet—which means the rate in the next 100 years would more than double the rate during the twentieth century. California is not generally as vulnerable as some of the eastern and southern states, which have low shorelines. But there are areas, such as the San Francisco Bay and the Delta, which are vulnerable. Since California is tectonically active, it is the combined effect of geologic change, rising or falling land, and global sea level rise, which matters. The effect of a rising ocean would be magnified where land subsidence is occurring and decreased where uplift is happening. Suggested items of research related to sea level rise are listed below.

4.4.1 Catalog Recent Historic Sea Level Trends along the Coast

A thorough survey of all the tide gage data and any other sea level references along the coast could produce a map containing recent decadal changes which would be helpful to land use agencies and developers along the coast.

The San Francisco Bay Conservation and Development Commission did something like this in 1988 for the Bay (SFBC and DC 1988). The California Coastal Commission has also produced a recent overview report on sea level rise (CCC 2001).

Research Needs

The objective of research in this area would be to catalog all available tide station data along the coast, in San Francisco Bay, and in the Delta. Some general information for four stations in California is contained in a Pew Center report on sea level rise (Pew 2000). Long-term data is needed (at least 20 years and preferably 50 years) to look for apparent trends in mean annual sea level. Presumably, an average of trends from San Francisco at the Golden Gate (Presidio gage) and from San Diego could be used to represent global sea level rise. Departure from that rate would be due to tectonic activity, or possibly some other effect such as oil and gas extraction. The catalog would establish a useful base to guide government and developers in the coastal zone. This survey should be conducted in the next few years.

4.4.2 Evaluate the Golden Gate Tide Gage Datum

Since the Golden Gate tide gage is the key reference point for so many sea level determinations (i.e., the central California coast, the Bay, and the Delta), it is essential that a determination of its vertical stability be made, checking for long-term vertical movement of the datum. Tools to do so may now be available by use of highly precise space geodetic techniques, such as Global Positioning Systems (GPS) and the International Terrestrial Reference Frame (ITRF), which can measure very small changes in vertical elevation. Point Blunt on Angel Island is one of the continuously operating reference stations (CORS), with an accuracy on the order of one centimeter.

Research Needs

A check on the Golden Gate tide gage datum would logically proceed in three stages: (1) compare previous precise leveling where the Golden Gate gage can be compared to nearby benchmarks (i.e., solid rock); (2) investigate whether the GPS system can be used for a precise determination of the elevation of the Golden Gate tide gage datum and its changes (if any) over time, and how long such measurements would need to be to instill confidence of a change that could be less than 2 mm (0.007 feet) per year; and (3) perform the measurements of actual tide gage datum elevations over a period of time, probably years.

The first stage could be accomplished in a year or two, the second (on which there is some doubt as to feasibility) and third could take several years of measurements.

It is recommended that the National Geodetic Survey or National Ocean Service investigate the feasibility of such a determination for the Golden Gate gage.[3] There have been claims that the apparent slow rise in sea level measured at the Golden Gate is due to settlement of the pier and tectonic movement. The precise determination, which may require several years, should lay this matter to rest.[4]

4.4.3 Effect of Higher Sea Level on Delta Levee Stability

Many levees in the Sacramento-San Joaquin River Delta are built on soft peat soil foundations. Historically, during high water at times of flooding, levees have burst with subsequent inundations of Delta islands. Sometimes this has happened during the summer, when channel stages are not unusually high. Rising sea level means channel levels in the Delta too will rise by a similar amount, increasing the risk of levee failure unless they are strengthened. Short-term changes in sea level due to El Niño events have the same effect, so changes in the frequency or intensity of El Niño events with climate change will also affect the risk of levee failure. The increase in horizontal pressure on a levee increases by the square of the increase in stage. For example, a levee withstanding four feet of water has to withstand 500 pounds of hydraulic force per linear foot of levee. But doubling the depth of water to eight feet increases the force to 2000 pounds per linear foot. Subsidence within the islands is also adding to the levee stability problem.

Research Needs

Researchers should conduct an analysis of the risk of failure for base (present) conditions, for a 0.5 feet rise (predicted at about the 2050 time frame) and a one-foot rise. Once this is done, an estimate of the change in risk due to El Niño events can be made. Some studies of levee stability were made by the Corps of Engineers in the early 1980s. A recent report was made for the CALFED Bay-Delta Program in April 2000 on seismic vulnerability of Delta levees (Torres, R. A. et al. 2000). This study showed that the greatest threat is present in the western Delta islands.

4.4.4 Salinity Intrusion

The larger factor in increasing ocean salinity intrusion in the Delta would be a longer season of controlled relatively low outflow. Model studies of the CVP-SWP system

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[3] Potential contacts for work in this area would be Dr. Dennis Milbert, Chief Geodesist, National Geodetic Survey, in Silver Spring, Maryland; Marti Ikehara, California State advisor in Sacramento (office located in Caltrans); and Dr. Chris Zervas, with the National Oceanic and Atmospheric Administration (NOAA).

[4] There were some interesting reports in 2001 about measuring small changes in ground movement in the Los Angeles region with this kind of technology, including the effect of groundwater storage and extraction on land surface elevations in *Science News,* August 25, 2001, and in *Nature* magazine and also the USGS earthquake Web page.

referred to in the water supply section are needed to estimate the probable decrease in spring and early summer outflow as a result of decreased snowmelt. There is a tradeoff. Under present rules of operation, the effect in some months could be additional outflow, rather than degradation of water quality at the export pumps in the south Delta.

Scripps has done work also on salinity intrusion in the San Francisco Bay system (Knowles and Cayan 2001).

Research Needs

A separate determination of the Bay Delta system should be made with salinity models to see how much difference it would make if channels were 0.5 and 1.0 foot deeper because of ocean rise. The Scripps model may be useful in evaluating longer periods of low outflow. The more detailed modeling of smaller differences in channel depth and salinity in the Delta itself will probably require more elaborate models such as those used by DWR.

4.4.5 Silt Deposition in the Delta

The amount of silt carried into the Delta by major rivers and the amount leaving the Delta for the Bay at Chipps Island will be highly variable from year to year, depending on flood flows. The difference presumably is being deposited in Delta channels and may be enough to offset rising sea level, thereby neutralizing the depth element of additional salinity intrusion.

The USGS has been measuring sediment flow in the major rivers and the Bay. The measurement program has been conducted by scientists in the USGS Sacramento office who have been working on sediment movement.[5]

Research Needs

The amount of silt carried into the Delta by major rivers and the amount leaving the Delta for the Bay at Chipps Island should be monitored. The USGS has been measuring sediment flow in the major rivers and the Bay, and this work should continue. PIER should encourage the USGS to maintain funding of this important data collection and analysis activity.

4.4.6 Catalog of Vulnerability of Coastal Marshes and Wetlands

It is as yet unclear whether coastal marshes and wetlands (many of which are partially protected by low levees) may have problems with rising sea level and how soon such problems could arise. Cataloging historical sea level changes could provide a basis for evaluating this issue.

On its Web site, the Coastal Conservancy has information and maps of 41 coastal wetlands in southern California between the Mexican border and Point Conception in Santa Barbara

[5] Principal scientists are Randall Dinehart and David Schoellhamer.

County. This inventory is a good start and an example of what can be done for the remainder of the State. Some added analysis appears to be needed to address the vulnerability of these 41 marshes to sea level rise.

Research Needs

Projections from the recent historical sea level change would be the basis for determining whether coastal marshes and wetlands may have problems with rising sea level and how soon such problems could arise. The catalog should try to indicate whether future problems would be the result of higher water levels or more salt-water intrusion. This research should use the Coastal Conservancy's coastal wetlands data as a starting point. Remotely sensed data can provide updated information on land surface characteristics at fine scale.

4.4.7 Coastal Aquifer Salinity Intrusion

Seawater intrusion is already a problem for several California coastal basin groundwater aquifers, because water levels have been pumped below sea level inland, and there are subsurface connections between the aquifer and the sea. Higher ocean levels will increase the intrusion slightly. The simplest strategy is to keep inland water tables above sea level. In some places, a line of freshwater injection wells has halted seawater intrusion. A pumping trough (line of pumped wells) to stop the inland flow of salt water and create a seaward flow underground in a strip of land near the shore has been proposed in Ventura County as an alternative to injection wells.

Sea level rise adds to the problem, but only slightly. Oceans are not expected to rise at a rate of over 0.01 feet per year, at least to the year 2050. That rate would be about 1.5 times the apparent rate of the last several decades on the California coast. Calculating the effect of 0.01 feet per year on a fairly good-sized aquifer of 200,000 acres (about 10 by 30 miles), with a specific yield of 0.1, works out to only 200 acre-feet per year. That amount would be only a tiny fraction of the likely safe yield, which for a basin of this size could easily be over 100,000 acre-feet per year. The conclusion is that coastal aquifer additional salinity intrusion is not likely to be significant in California, but there may be a few areas where the encroachment would be a problem.

There may be more complications to underground water movement and water quality in multiple aquifer systems. The USGS office in San Diego, has made detailed studies of the Ventura County coastal aquifer, a multiple aquifer system.[6]

Research Needs

Although it does not appear to be a high climate-change priority, a test study of a multiple aquifer coastal system should be undertaken to better quantify whether a significant problem could develop due to sea level rise.

[6] Mr. Randall Hanson would be a potential contact.

4.4.8 Grade Line of Sewers and Storm Drains

In coastal and bay cities, storm drainage and treated sewage often discharge to salt water via gravity. In those cases, higher ocean levels eventually may cause some flow capacity problems. Solutions could be low-lift pumps or perhaps more pipeline capacity for drainage. Storage during high tide may be another option for certain users.

Research Needs
It would be good to identify where the gravity (or flap gate) drains are, but this is not likely to be a near-term issue, because of the slow rise in sea level estimated at less than 0.1 foot per decade.

4.4.9 Coastal Erosion

Much of the coastal erosion occurs during major storms and high tides. The sea has been eroding coastal bluffs for centuries. The process will accelerate with sea level rise. Most of the vulnerable areas have been identified. To the extent possible, it is wise to keep roads and infrastructure far enough back to provide a cushion for erosion. Shoreline protection is possible, but very expensive.

Research Needs
Changes, particularly where there are sand barriers and lagoons, are likely to be sudden, happening during major storm events. Some research in areas along the California coast judged vulnerable to rapid changes is desirable to better assess this threat (Thieler and Hammer-Klose 2001). Paleostudies reaching back to former millennia, when sea level rise was more rapid, have yielded useful information on the Texas Gulf of Mexico and East Coast. (Anderson, Rodriguez, Fletcher, and Fitzgerald 2001). Similar paleostudies may be worthwhile in California.

4.5 More Intense Precipitation Events

In a warmer world, some increase in the intensity of major precipitation events would be expected, because warm air can hold more water vapor than cooler air. Lifting of the air by mountain ranges, storm frontal activity, or convection (thunderstorms) has the potential to increase rain intensity. There is no reason to believe that California would be any more subject to hurricanes and tropical storms than today.

4.5.1 Risk of Bigger Floods and Extreme Precipitation

More intense precipitation (on the order of 10% for a 3°C rise) would generate larger floods. Another factor on streams draining high mountain areas is that many storms now produce a mix of rain with snow on the higher parts of the watershed. A warmer climate means that a greater proportion of a storm precipitation is likely to be rain, producing more direct rain runoff. Where reservoir flood control is part of the flood management structure, most storms will still be controlled to safe discharge by the dam. One of the leading climate models suggests that El Niños may be more frequent, which could generate more frequent heavy storms in southern and central California.

Currently, reserved storage space during the winter may not be adequate for the larger storms. The result is that the degree of protection would gradually shrink. Additional flood control storage or added downstream channel conveyance capacity can be expensive. The Central Valley, in particular, has already seen a round of resizing flood protection on major rivers with numerous other studies underway. Global warming suggests that under sizing may still be a problem. Perhaps the comprehensive flood study (Corps of Engineers 2000) now being conducted by the U.S. Corps of Engineers and the (State) Reclamation Board needs to consider adding an additional allowance of say, 10%, to handle possible global warming. The cost of doing so may be in the billions.

Research Needs

As GCMs are developed and improved, researchers must analyze precipitation results to see if there is a consistent trend for more intense storms and extreme precipitation events in California. There are indications of such trends in the work of Dr. Michael Dettinger of Scripps/USGS and Dr. Norman Miller of LBNL, in their downscaling of the Hadley and Canadian GCM model runs used in the National Assessment.

4.5.2 Revise Depth-Duration-Frequency Data

Some of the most useful rainfall statistics are the rainfall depth-duration-frequency data used by many engineers and designers for storm drains, culverts, roofs, and a host of works. These are the curves, for example, which show that the 1-in-25-year storm can produce 2 inches in 2 hours at a particular place. Figure 4 shows an example for Blue Canyon northeast of Sacramento, which is a wet location. One can go to a chart like this, pick an interval of time, and determine the inches of precipitation to expect on a given return frequency.

If storm intensity increases as a result of climate change, these curves, and the structures built with their guidance, will be out of date with less protection than intended.

This kind of work is done by the DWR. Thanks to analysis of hundreds of precipitation station records by former State Climatologist James Goodridge, the DWR has a large database of short-period (24 hours or less) and long-period statistics, which is made available to requestors. The statistics are based on the historical records of precipitation, which may be gradually changing.

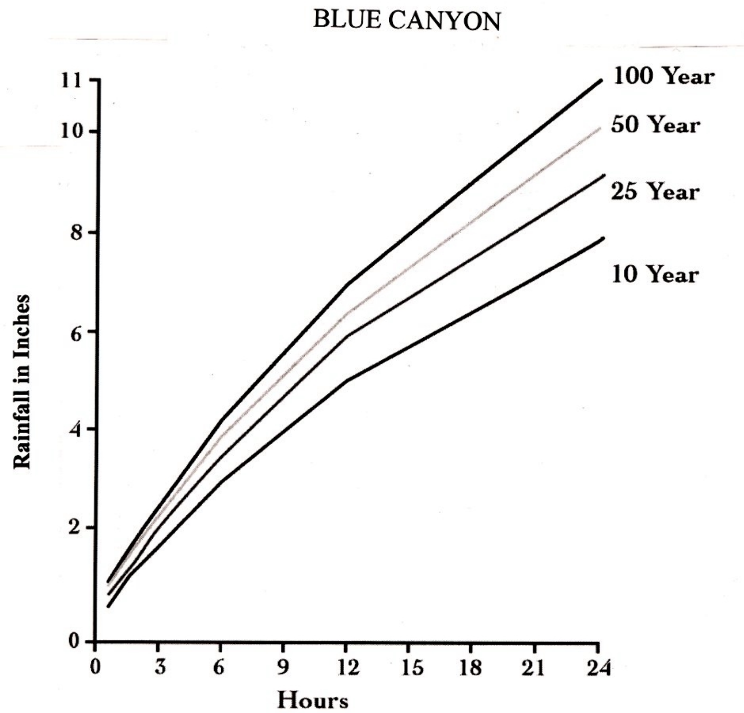

Figure 5. Depth-Duration-Frequency Curves for Blue Canyon

Source: DWR records.

Research Needs

Updating depth-duration-frequency rainfall data (or at least incorporating the data from recent storms) should be a high priority for the DWR. Practitioners may wish to incorporate a safety factor in their designs in recognition that long-term projects may be operating in a climate that can produce more intense storms.

The goal would be to prepare and maintain updated depth-duration-frequency files for the hundreds of stations in California and to post this data on the Web for Internet access. Thus designers would have ready access to the best information. This activity would require continuing funding to maintain and update the database. Preparing data for Web access should have highest priority in the next two years.[7]

It is possible that some estimates of the increase in storm intensity could be gleaned, for selected regions, from the GCM or regional climate models. It is not likely that confidence can be placed in absolute model results, but the relative comparisons of current and future GCM climate scenarios may be reasonable. When more consistent GCM precipitation results are available (probably in several years), PIER could fund a comparison study.

[7] DWR does not seem to have funding for this effort, although another funding entity could jumpstart the process during the next two years. The estimated cost would be $250,000 for the first year and $150,000 the second year.

4.5.3 Bigger Probable Maximum Floods

If extreme precipitation events are larger, one could also expect an increase in the probable maximum floods used for dam spillway design. The probable maximum flood (PMF) is the largest flood believed to be meteorologically possible in a region. It is developed by an analysis of the most severe historical storms, looking at winds, dewpoints, temperature, and storm type, then maximizing the rain producing potential by adjusting those parameters to the highest reasonable value for an area.

A warmer climate means these rare storms would have more moisture potential. Whether the wind and storm track would be the same is not certain, but a reasonable assumption is that not much change could be expected. The general southwesterly fetch storms, which currently cause the major floods, are still expected to be the type that would cause the PMF on a large watershed.

Owners of large dams periodically reevaluate their PMF and other dam safety factors. They should be made aware of the potential for somewhat larger future PMFs, especially if their spillway is only marginally acceptable. The DWR Division of Safety of Dams is in charge of the inspection of all non-federal dams in California, about 1200 in all.

Research Needs
Because GCM precipitation results are not regarded as reliable yet, there are no immediate research suggestions. In 5 to 10 years, when GCM precipitation is expected to be better, there may be a need to examine potential PMF changes where dam and spillway modification work is planned.

4.5.4 Erosion Potential

Storms with greater intensity tend to cause the most erosion. Hence, on average, greater amounts of sediment would be expected with an increase in strong precipitation events. But it may be difficult to discern the natural increase in view of all the disturbances of an increasing human population. Mountain and foothill reservoirs could see some increase in sedimentation rates.

Research Needs
The research need is to determine how vulnerable mountain watersheds would be to erosion if rainfall were to intensify. This effort is closely tied to the transition zone erosion entry under Section 4.7.2. The American River Watershed Institute in Auburn is currently partnering with the Placer County Water Agency to seek support for a paired watershed study of climate changes on Duncan and Long Canyon near French Meadows reservoir. Financial help by PIER could get the study under way. These two watersheds do have a good history of hydrologic measurements.

4.6 Water Use

There are likely to be changes in the water *use* side of the equation, as well as in water *supply.* Water consumption changes may be small, but because so much land area is involved, amounts could be very significant. Generally, a slightly warmer climate with less frost and a higher atmospheric concentration of carbon dioxide is regarded as beneficial to most food crops.

4.6.1 Change in Crop Evapotranspiration and Water Requirements

As a rule, plant evapotranspiration (ET) goes up with increasing temperature. Higher carbon dioxide levels, however, reduce water consumption (at least in laboratory tests) and seem to increase yield. In the opinion of knowledgeable researchers, the higher water consumption with warmer temperatures will probably only be partially offset by the carbon-dioxide-based reductions. The net result will be slightly higher water requirements. The situation is complicated for some of the annual crops. Here it may be possible to change the season a few weeks, which may result in no net change in water use. Tomatoes are one example. But often marketing and processing windows for produce set the planting time, limiting the farmer's flexibility.

Research Needs

The whole subject of potential crop ET and water requirements is an important area of research for university and Agriculture Extension Service people. In view of further cuts in water availability to California agriculture, changes in ET would be of great importance.

The goal would be to assess likely changes in ET in a year 2050 or 2100 scenario, with warmer average temperatures and a higher carbon dioxide content of the atmosphere. To do this, we need some reasonable median-type projections of weather by GCM modelers, and it may require new plant water consumption measurements by realistic field type experiments.

4.6.2 Indication of Recent Changes in ET

Since carbon dioxide concentrations have increased about 20% over the last 40 years, one wonders whether there is any noticeable effect on ET, especially the measured reference ET of grass, ETo. In the 1960s there were a number of well-measured grass lysimeters in various locations in California measuring directly, by weight changes, the water consumption of grass.

Research Needs

The University of California, in cooperation with DWR, should reinstall a couple of lysimeters and repeat, as closely as possible, the former measurements. Actual ET varies somewhat from year to year and day to day, depending on weather conditions. So it would probably take three to five years to see if there is a noticeable change. It is recommended that the lysimeters at Davis and the former site at Five Points in the San Joaquin Valley be reactivated to carefully measure actual water consumption for comparison with earlier decades. The result would be field evidence of changes, if any, in plant water use due to the modest change in atmospheric carbon dioxide during the past 40 years. As a minimum, the two named lysimeters should be operated for ten years. It may take five to ten years to develop good comparable data because of the seasonal and yearly natural variations. It is also quite possible that higher carbon dioxide is a factor in the continuing improvement in California crop yields. Some university technical expertise could be directed to answering this question.

4.6.3 Change in Growing Season

Warmer climatic conditions should enable some change in the planting and growing season for annual crops. There should be more possibilities for double cropping. Many vegetables are already multiple cropped. Double cropping increases the water use of an acre; however, more produce is grown from the same acre. Market and food processing limits are also a factor in growing season determinations.

Less frost, if that happens, could increase the range of sensitive crops. For example, the orange belt in the San Joaquin Valley may be able to expand higher into the foothills and also northward. There may be some expansion too of the range of wine grape production in higher coastal and foothill valleys.

Research Needs
The California Department of Food and Agriculture should study potential cropping and growing season changes that fit a global warming scenario. As input, the climate modelers will need to be as specific as possible on changes in minimum temperatures and frost risks, as well as on the extent of extreme summer heat.

4.6.4 Effect of Changes in Winter ET on Aquifer Recharge

For many California groundwater aquifers, a significant portion of recharge comes from deep percolation of precipitation below the rooting zone, whether that of native vegetation or farmland. Temperatures several degrees warmer during the winter rainy season can be expected to increase ET, thereby drying out the soil more between storms. As a result, greater amounts of rain in subsequent storms would be needed to wet the root zone and yield excess for deep percolation. Thus, there could be fewer instances of winter percolation and a potential significant loss of natural recharge. Water users and agencies overlying groundwater basins should keep this in mind when evaluating adequacy of future supplies.

Research Needs
When future precipitation can be predicted with more confidence by the atmospheric climate models, analysis of a couple of groundwater basins in California can be made, comparing historical regimes with likely future scenarios. Since vegetation ET, whether native or planted, is an important element, this analysis should await estimates of likely changes in ET developed by research in Section 4.6.1. Because of ongoing work by

Randall Hanson, of the USGS in Ventura County groundwater basins, these basins could rank high for an initial assessment.

4.7 Other Items for Research

Items for research that do not fit well under the preceding categories are included here.

4.7.1 Water Temperature

Warmer air will make it more difficult to maintain rivers cold enough for cold-water fish, including anadromous fish. With reduced snowmelt, existing cold-water pools behind major foothill dams are likely to shrink. As a result, river water temperature could warm beyond a point that is tolerable for the salmon and steelhead that currently stay in these rivers during the summer. It is doubtful that the existing cold-water temperature standards in the upper Sacramento River could be maintained. Problems are likely for juvenile steelhead, as well.

As part of the Oroville power plants relicensing project, DWR plans to investigate existing water temperature models and possibly develop new models for Lake Oroville and the downstream Feather River. Once these tools are selected or developed, other researchers can apply them to other streams and reservoirs and begin to evaluate effects of changed climate scenarios. A need will still exist, however, to model the temperature of foothill reservoir inflow with changed climate scenarios.

Research Needs

There are several existing models of water temperature in reservoirs and downstream rivers. The primary one being used operationally is the U.S. Bureau of Reclamation monthly temperature model of the Sacramento River basin (USBR 1990).[8] This model was originally developed by the Corps of Engineers Hydrologic Engineering Center in Davis. There is a need for better models.

Researchers should analyze selected foothill reservoirs to see what a different pattern of inflow would do to temperatures in the reservoir and in the rivers below. Some have advocated planting tall trees on the riverbanks to provide more shade. Researchers should evaluate the effectiveness of doing so, as well as the conflict with flood control purposes of tall trees in leveed reaches. There may also be a need for more basic temperature data at various depths in existing reservoirs and along streams to calibrate models.

4.7.2 Transition Zone Erosion

If the snow line rises as much as 1,500 feet, a substantial zone of the Sierra and other higher mountains will see much more winter rain instead of snow. The increased direct runoff is likely to produce more erosion than the gradual runoff from melting snow. This

[8] A contact for this work is Russ Yaworsky in the Mid-Pacific Region office in Sacramento.

is obvious from the brown water typical of lower elevation river flow during a major winter storm, as opposed to the cleaner water typical of flow from spring snowmelt.

Research Needs
Researchers should study measures that could reduce winter sediment production from the transition zone. This could be an element of study that PIER could support in the proposed American River Watershed Institute paired study of two streams that was mentioned previously.

4.7.3 Water Weeds

A longer season of growth and a greater range can be expected for aquatic nuisance plants like hydrilla, pond weed (egeria densa), and water hyacinth. Cold temperatures inhibit the growth of these weeds. Currently they are controlled by mechanical means or by spraying. A special sterile triploid carp has provided good control of hydrilla in the canals of the Imperial Irrigation District. Related problems occur with invasive exotic riparian nuisance plants like arundo and salt cedar (tamarisk).

Research Needs
Research into means of control for these and other non-native aquatic weeds would be useful.

4.7.4 Increased Smog

Warmer air temperatures cause increased ozone and smog if the other atmospheric ingredients are there. The water-related issue is whether such a regime would significantly affect crop choices in some areas for farmers. The pollutants in the air may also have some effect on stream and lake water quality.

Research Needs
No immediate research is suggested on this item. But studies of atmospheric changes should be monitored and if pollution is foreseen, particularly ozone, to the extent it would significantly affect common crops, a study of potential change in cropping patterns and associated water use would be warranted.

4.7.5 Wildfires

Warmer temperatures and a longer period of dry soils during summer in the mountains could mean a greater wildfire hazard and eventual change in watershed vegetation cover. Such changes are also likely to change the runoff characteristics of the mountain watersheds, again adding sediment to the runoff. Plant life zones can be expected to shift upward. Higher carbon dioxide concentrations could promote greater chaparral growth if winter rains are adequate, increasing fuel loads. Some of the climate scenarios project more winter precipitation, especially in the southern half of California. That, along with higher carbon dioxide in the air, could further increase biomass production.

Wildfire is a natural and necessary element of many California ecosystems. Nearly a century of wildfire suppression has resulted in heavy biomass accumulations fueling a growing incidence of catastrophic, stand-replacing fires, and in widespread changes in the species composition of ecosystems. Current fire and ecosystem management policy contemplates large-scale ecosystem restoration, involving prescribed fires and mechanical fuel reductions on millions of acres and the subsequent reintroduction of sustainable fire regimes. Success of this policy depends critically on understanding past and present fire regimes, as well as understanding how climate variability and change may constrain future fire regimes and ecosystems.

Research Needs

Archival records of modern wildfire regimes need to be integrated with paleo-reconstructions of wildfires of the past in order to distinguish between the influence of climate and of management on wildfire risk. Wildfire and ecosystems management would benefit from a GIS-based model of wildfire risk that incorporates climatological and ecological changes with projections of development and population growth.

Studies of the change in wildfire risk and eventual shifts in vegetation should be undertaken. These vegetation shifts could affect runoff; greater fire frequency would probably increase sediment production, which would cause an increase in sediment buildup in downstream reservoirs. There may be wildland management practices that would counteract the trend. These practices would also need to be evaluated and tested in the field.

Again, if the American River Watershed Institute is successful in obtaining funds for its proposed paired watershed study at Duncan and Long Canyon Creeks, insights into fire induced changes may be forthcoming. Substantial portions of these two watershed were burned during the summer of 2001.

4.7.6 Increased Salinity

If temperatures go up, evaporation from reservoirs and other water surfaces will increase. Typically now, reservoir evaporation is only a few percent of total flow so the effect probably would be minor. There may not be an effect if lower reservoir levels prevail in the summer. However, if ET rates go up, a slightly greater fraction of the total moisture will transpire into the air and the drainage fraction left behind will have slightly more salts. For most of California, these kinds of water quality changes are likely to be small , but with a slight tendency toward degradation of fresh water sources. One area in California where there could be more significant problems is the lower San Joaquin River region, which may affect total maximum daily load (TMDL) limits.

Research Needs

Scientists at LBNL's Water Resources Research and Application Center in Berkeley[9] have much experience on analysis and modeling of salt and other constituents in the lower San Joaquin River system. There is merit to examining the potential for significant salinity changes on both the lower San Joaquin River and on the Colorado River. The Santa Ana River of southern California would also be a good candidate in view of its importance in recharge of the Orange County aquifer.

4.7.7 Impacts on Drinking Water Treatment

Trihalomethanes are undesirable byproducts of drinking water disinfection when chlorine is used in the presence of organic carbon. This production can be aggravated by bromide in the water supply. Urban water supplies would see a slightly greater risk of trihalomethane production in water treatment simply because the water would be warmer, which enhances trihalomethanes. Warmer water tends to have more pathogens as well, which can increase treatment costs. Solutions would be to reduce dissolved organic carbon in water supplies and possibly other methods of water treatment. However, there are many places in the world that successfully treat warmer water than California is likely to see into safe drinking water. So this should not be a major problem; satisfactory technology already exists to take care of it.

Research Needs

Because of the long range potential to affect costs and possibly methods of drinking water treatment, it would be useful to have some research on the potential effects on water treatment. A survey of practices in the southern United States and abroad should reveal how they have adapted to warmer water temperatures. Another aspect is potential changes in seasonal timing of organic carbon and bromine in Delta export water supplies.

5. Goals

The goal of the Water Resources portion of the PIER Climate Change Research Plan is to help California make decisions about water management that will protect the health and vitality of its population, ecosystems, economy, and power generation. The achievement of that goal depends on the ability to predict the effects of climate change on water supply, timing, and use.

The PIERA program recognizes that much work is currently under way in these areas and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIEREA will identify existing efforts and form partnerships to leverage resources.

[9] A contact is Dr. Nigel Quinn.

5.1 Short-term Objectives[10]

The priority in water resources research should go to areas that: (1) are foundational to measuring or projecting climate change, (2) are likely to show significant effect on water resources or water use, and (3) have been identified by previous studies as being more vulnerable to problems than other areas. A second priority would be to conduct projects that are expected to yield results in a few years. The selection of the priority short-term research objections are the author's, but do reflect discussion with people in the water resources planning and project operations community.

5.1.1 Monitoring

A. Support the regular, consistent, and sustained measurement of hydrologically important variables such as precipitation and other climate data, streamflow, snowpack, and ocean and Delta tide levels.

Activities needed: (1) Support the National Weather Service's Climate Services Division in developing and operating California weather stations as part of its national climate reference network of weather stations. (2) Increase the measurements in the high Sierra snow zone, including some discrete new sites in wilderness areas.

Critical Factors for Success:
- Continued funding of the monitoring activities.

5.1.2 Depth-Duration-Frequency Data

A. Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data.

Activities needed: (1) Coordinate collection and updating depth-duration-frequency rainfall data with the Department of Water Resources. (2) Update depth-duration-frequency rainfall data. (3) Design and develop a Web-based database for dissemination of this data. (4) Maintain and update the database at intervals to be determined by DWR and PIER.

Critical Factors for Success:
- Adequate funding

[10] S*hort-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

5.1.3 Testing Operation of the CVP-SWP System

A. Conduct a simple test of the impact on water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume and timing.

Activities needed: (1) Using DWR's CALSIM II model, run a simple test of the impact on water supply of a possible 3°C higher temperature climate scenario, assuming precipitation similar to the historical amounts, except warmer. (2) Confirm the estimates with the U.C. Davis CALVIN model.

B. Conduct detailed tests of the impact on water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume.

Activities needed: (1) Determine which model is best for developing input to the CALSIM II model, using results from watershed models such as PRMS with basic input from several GCM runs; the procedures and detailed watershed models, essentially NWSRFS, being used by Norman Miller's group in the LBNL Water Resources Research and Applications Center; or some other models that can convert GCM output into watershed runoff by month. (2) Using the selected model, run a more detailed test of the impact on water supply of a possible 3°C warmer climate scenario, conducting several runs, with varying wet and dry GCM scenarios, to produce year-by-year results over a long hydrologic base period. Include higher salinity control requirements in the western Delta as appropriate to the scenario.

Critical Factors for Success:

- The detailed tests would require a major effort by the modeling staff of DWR or any other agency that might conduct the studies with large resource inputs during the next several years.

5.1.4 Future Precipitation

A. Support the development of global climate models that can better predict future precipitation in California.

Activities needed: (1) Support of U.C. and National Laboratory experts (Scripps, UCLA, Livermore, Berkeley and elsewhere) in analyzing results of newer GCM runs by the major modeling centers of the world as they apply to California, especially in simulating historical precipitation and predicting future precipitation. Encourage feedback from these experts to the GCM modelers.

Critical Factors for Success:

- Development of models (or downscaled models) that do a reasonable job of simulating present climate patterns at the watershed level.

5.1.5 Evaluate Golden Gate Tide Gage Datum

A. Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage.

Activities needed: (1) Compare the datum elevation of the gage with nearby benchmarks sited on solid rock. (2) Compare the precise vertical elevations using a satellite GPS system.

Critical Factors for Success: The assistance of the National Geodetic Survey is essential in conducting the surveys and performing the measurements.

5.1.6 Catalog Sea Level Trends Along the Coast

A. Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast.

Activities needed: (1) Conduct a thorough survey of all the tide gage data and any other sea level references along the coast to determine apparent trends in sea level in recent decades. The map of the San Francisco Bay developed by the San Francisco Bay Conservation and Development Commission in 1988 can be a useful sample guide. The California Coastal Commission in San Francisco[11] also has data and may be willing to share in this study. Scripps Institution of Oceanography and the National Ocean Service also may be able to help.

Critical Factors for Success:

- Collection of tide gage data would require the cooperation of the several agencies mentioned above and should be documented in a detailed report.

5.1.7 Recent Changes in Evapotranspiration (ET)

A. Measure current evapotranspiration to compare current data with earlier data.

Activities needed: (1) Identify existing lysimeters in California. (2) Reinstall or reoperate lysimeters at Davis and Five Points, and maintain any other ones left from the 1960s and 1970s. (3) Maintain lysimeter operation for ten years, to account for seasonal and yearly natural variations.

Critical Factors for Success:

- Reinstatement and measurement at these two locations would require the assistance and cooperation of the University of California, Davis, and DWR land and water use analysts.

[11] Lesley Ewing is a contact.

5.1.8 Estimate Change in ET and Crop Water Requirements

A. Assess likely changes in ET in a year 2050 or 2100 scenario, with warmer average temperatures and higher carbon dioxide content of the atmosphere.

Activities needed: (1) Obtain reasonable median-type regional projections of weather, primarily temperature, from GCM modelers. (2) Have knowledgeable experts in plant water consumption at the University of California and Agricultural Extension Service and land and water use analysts in DWR estimate likely future ET rates for the major California crops by region.

Critical Factors for Success:

- Sufficient funds or grants to enable experts in government and the University system to do the necessary studies. The climate modelers need to provide likely temperatures and monthly precipitation in major agricultural areas.

5.1.9 Winter Flood Control Space

A. Conduct a systematic review and evaluation of the effect of climate change on major multipurpose flood control reservoirs.

Activities needed: (1) Conduct a systematic review and analysis of the likely increase in flood control needs with climate change on all the major flood control reservoirs in California and their ability to provide the protection in the original design, in a 1-in-100-year flood, and in a 1-in-200-year flood. (2) Determine whether it is feasible to expand flood control space in reservoirs deemed inadequate. (3) Determine whether changes in flood operation rules can help to handle bigger floods.

Critical Factors for Success:

- Some of this evaluation can be produced by the modified CALSIM II test studies of the CVP-SWP system. For the Central Valley, it would be best to await the comprehensive Flood Study findings (to use as a base).

5.1.10 Water Temperature Modeling in Rivers

A. Model water temperatures in both regulated rivers and natural streams.

Activities needed: (1) Identify rivers to model. The Feather River would be a good start in view of DWR's Oroville power relicensing study plans. (2) Collect more basic temperature data at various depths in existing reservoirs to calibrate models. (3) Model water temperatures in the rivers and streams selected. (4) Evaluate the effectiveness of potential countermeasures to unacceptable temperatures.

Critical Factors for Success:

- Development of a successful water temperature model of the Feather River and Oroville reservoir, which is anticipated as part of the power relicensing studies now underway.

5.1.11 Effect of Climate Change on Adjoining Regions

A. **Support monitoring of studies and research on climate change effect on runoff in the adjoining Pacific Northwest and Colorado River regions.**

Activities needed: (1)Monitor results of anticipated studies by others on climate change effects on runoff in the Colorado River and Pacific Northwest regions. Changes there could affect California water and power supplies.

Critical Factors for Success:

- A basic assumption is that interests in the Colorado River basin or service area will sponsor new studies. Likewise, Pacific Northwest interests would be presumably doing the same in that region. If this does not happen, then California ought to sponsor analyses of likely runoff changes on the Colorado River, which would be of higher priority, because it supplies water to Southern California.

Table 3. Short-term Budget

Objective	Projected Cost ($000)
5.1.1.A Support the regular, consistent, and sustained measurement of hydrologically important variables	1500*
5.1.2.A Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data	500
5.1.3.A Conduct a simple test of the impact on water supply of the CVP-SWP system of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume and timing	600
5.1.3.B Conduct detailed tests of the impact on CVP-SWP system water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume, including likely upstream reservoir operational changes	1,400
5.1.4.A Support the development of global climate models that can better predict future precipitation in California	1,000
5.1.5.A Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage	100*
5.1.6.A Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast	200
5.1.7.A Measure current evapotranspiration (ET)to compare current data with earlier data	500
5.1.8.A Assess likely changes in ET in a year 2050 or 2100 scenario with warmer average temperatures and higher carbon dioxide content of the atmosphere.	300
5.1.9.A Conduct a systematic review and evaluation of flood protection adequacy in major multipurpose flood control reservoirs under projected climate scenarios	600*
5.1.10.A Model water temperatures in both regulated rivers and natural streams	400*
5.1.11.A Support monitoring of studies and research on climate change effect on runoff in the adjoining Pacific Northwest and Colorado River regions.	200*
Total Short-term Cost	**7,300**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's total projected expenditure to complete each objective (over a three-year period).

Estimates of short-term costs to PIER and the California Energy Commission over the next three-year period are provided in Table 3. These are the author's estimates, made after consulting with others in the field, and represent approximate amounts to carry out the 12 previously listed short-term research objectives. Confidence in the cost figures is low, in view of uncertainties.

5.2 Mid-term Objectives

The foregoing items were judged of higher priority by the author, reflecting discussions with water resources specialists in State government and some local districts. It is recognized that priorities could be changed by events (such as floods and droughts) during the next couple of years. The mid-term objectives were discussed at more length in Section 4. They should begin in the 3- to 10-year time frame, although some profitable work could begin sooner if funds are available.

5.2.1 Loss of hydro at foothill reservoirs

5.2.2 Impact on reservoir recreation

5.2.3 Better understanding of hydrologic variability

5.2.4 Offstream storage (need more definitive runoff projections to do)

5.2.5 Changes in radiation

5.2.6 Delta levee stability with sea level rise

5.2.7 Catalog of vulnerability of coastal wetlands

5.2.8 Risk of bigger floods and extreme precipitation

5.2.9 Bigger probable maximum floods

5.2.10 Change in growing season

5.2.11 Water weeds

5.2.12 Effect of changes in winter ET on aquifer recharge

5.3 Long-term Objectives

Long-term research is judged of lower priority, either because of importance or because reasonable inputs in a projected changed climate would take some time to develop. These efforts are described in more detail in Section 4.

5.3.1 Natural groundwater recharge

5.3.2 Delta salinity intrusion

5.3.3 Silt deposition in the Delta

5.3.4 Coastal aquifer salinity intrusion

5.3.5 Grade line of sewers and storm drains:

5.3.6 Coastal erosion

5.3.7 Storm erosion potential

5.3.8 Transition zone erosion

5.3.9 Wildfire effects on watersheds

5.3.10 Increased river salinity

5.3.11 Impacts on drinking water treatment

6. Leveraging R&D Investments

6.1 Methods of Leveraging

Much of the work identified in this roadmap would be collaborative with other entities; PIEREA would either co-fund projects by other entities, or use outside funds to support PIEREA efforts. Specifically, this roadmap seeks to:

- provide PIER funds for co-funding existing or planned work,
- solicit funds from federal and private resources to build upon their efforts, or to co-design new projects at the Energy Commission, and
- provide seed money to begin items of research, with the goal of having others continue the effort once it is started.

6.2 Opportunities

Co-sponsored efforts are already under way with EPRI. Co-sponsorship opportunities are likely with the National Weather Service, Scripps Institution of Oceanography, LBNL, Lawrence Livermore National Lab, the National Center for Atmospheric Research, the USGS, the California Department of Water Resources, the University of California at Davis, the U.S. Corps of Engineers, the State Reclamation Board, the Georgia Institute of Technology, CALFED, the University of California at Santa Barbara, the San Francisco Bay Conservation and Development Commission, National Geodetic Survey, Caltrans, NOAA, EPRI, California Coastal Conservancy, and the California Department of Food and Agriculture. Each of these organizations is interested in addressing climate issues.

The California DWR is interested in research that could affect water planning and plans to make adaptation to climate change part of its Bulletin 160 discussions and work plans. DWR also proposes, if funding permits, to be active in monitoring and processing and disseminating depth-duration-frequency rainfall data. The following specific collaborative opportunities have been identified:

Monitoring

The National Weather Service, in its newly reorganized Climate Services Division, is developing a climate reference network of 250 weather stations as a national benchmark of long-term climate monitoring stations. Probably about five will be located in California, and PIER could cosponsor or co-fund work at those stations.

Water Supply
The California Energy Commission and EPRI are already evaluating water supply changes in California that may result from climate change.

- **Modeling Future Precipitation**
Scripps Institution and the Lawrence Berkeley National Lab have used GCM models developed by other institutions and downscaled them into regional climate models. PIER could leverage these efforts.

In addition, Lawrence Livermore and Lawrence Berkeley National Laboratories—in collaboration with the National Center for Atmospheric Research in Boulder and other groups—are working on a Community Climate System Model. PIER could support this work.

- **Snow Level Changes and Resulting Runoff Changes**
The USGS, the National Weather Service, Scripps Institution of Oceanography (Climate Research Division) and LBNL have all conducted work in this area. PIER should investigate potential co-funding or collaborations with these entities.

- **Test Operation of CVP-SWP System**
The California Department of Water Resources, the University of California at Davis, Lawrence Berkeley National Laboratory, and the Scripps Institution of Oceanography (Climate Research Division) may all offer collaborative or co-funding opportunities.

- **Impact on Reservoir Recreation**
The California Department of Water Resources could offer some collaborative or co-funding opportunities in this area.

- **Winter Flood Control Space**
The U.S. Corps of Engineers and the State Reclamation Board are engaged in a comprehensive study to improve flood management in the Sacramento and San Joaquin Valleys. The U.S. Bureau of Reclamation, with help from Utah State University, is testing a new approach to flood control at Folsom Reservoir.

Dr. Konstantine Georgakakos, Managing Director of the Hydrologic Research Center in San Diego, California and research scientist at the Scripps Institution of Oceanography has been evaluating this issue, as has Dr. Aris Georgakakos, Director of the Georgia Water Resources Institute and professor at the Georgia Institute of Technology.

- **Groundwater Recharge**
  The U.S. Geological Survey has been investigating recharge in Ventura County.

- **Offstream Storage**
  Work in this area would be based on previous CALFED work; therefore, PIER should approach CALFED for collaborative and co-funding opportunities.

- **Changes in Radiation**
  The University of California at Santa Barbara has conducted work in this area. Scripps Institution of Oceanography is beginning a data gathering effort in Yosemite National Park, with the cooperation of the NPS and others.

Loss of Hydro at Foothill Reservoirs
Work is under way by Dr. Jay Lund at UC Davis adapting the CALVIN model for power production from several multipurpose reservoir hydro units.

Sea Level Rise
- **Cataloging Recent Historic Sea Level Trends along the Coast:** The San Francisco Bay Conservation and Development Commission, the California Coastal Commission and Scripps Institution of Oceanography.
- **Evaluation of the Golden Gate Tide Gage Datum:** National Geodetic Survey; Caltrans; and NOAA
- **Higher Sea Level on Delta Levee Stability:** EPRI, DWR, CALFED, Scripps Institution of Oceanography
- **Salinity Intrusion:** Scripps Institution of Oceanography and the Department of Water Resources
- **Silt Deposition in the Delta:** U.S. Geologic Survey
- **Catalog of Vulnerability of Coastal Marshes and Wetlands:** California Coastal Conservancy
- **Coastal Aquifer Salinity Intrusion:** Department of Water Resources
- **Grade Line of Sewers and Storm Drains:** Major San Francisco Bay Area cities and East Bay Municipal Utility District
- **Coastal Erosion:** California Coastal Commission

More Intense Precipitation Events
- **Risk of Bigger Floods and Extreme Precipitation:** U.S. Corps of Engineers and The (State) Reclamation Board
- **Revise Depth-Duration-Frequency Data:** The Department of Water Resources
- **Bigger Probable Maximum Floods:** DWR Division of Safety of Dams
- **Erosion Potential:** American River Watershed Institute

Water Use

- **Change in Crop Evapotranspiration and Water Requirements:** Universities and Agriculture Extension Services
- **Indication of Recent Changes in ET:** University of California at Davis
- **Change in Growing Season:** California Department of Food and Agriculture
- **Aquifer Recharge:** Perhaps U. S. Geological Survey or DWR

Other Items for Research

- **Water Temperature:** DWR in its Oroville power relicensing study
- **Transition Zone Erosion:** Perhaps American River Watershed Institute
- **Water Weeds:** Irrigation districts
- **Increased Smog:** California Department of Food and Agriculture
- **Wildfires:** U.S. Forest Service, American River Watershed Institute, Scripps Institution of Oceanography
- **Increased Salinity:** Central Valley Regional Water Quality Control Board
- **Impacts on Drinking Water Treatment:** Metropolitan Water District of Southern California

7. Areas Not Addressed by This Roadmap

The suggested research plan has not intentionally avoided any aspects of California water resources associated with climate change.

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10. Technical Persons Contacted

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Dr. Thomas Wigley, National Center for Atmospheric Research, Boulder, Colorado – Global and regional climate models

Dr. Kathleen Miller, National Center for Atmospheric Research, Boulder, Colorado – Global and regional climate models

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Dr. Dan Cayan, Scripps Institution of Oceanography, U. C. San Diego, La Jolla, California – Global and regional climate models

Dr. Alan Sanstad, Lawrence Berkeley National Lab, Berkeley, California – Economics

Dr. Richard Howitt, University of California at Davis – Economic modeling

Walter Ward, Modesto Irrigation District, Modesto, California – Water operations

Joe Lima, Modesto Irrigation District, Modesto, California – Water operations

Wilton Fryer, Turlock Irrigation District, Turlock, California – Water planning

August 2001

Dr. Larry Gates, Lawrence Livermore National Lab, Livermore, California – GCM modeling.

Dr. Robert Livezey, National Weather Service, Camp Springs, Maryland – Weather data.

Charles Hakkarian, EPRI, Palo Alto, California – GCM modeling.

Dr. Norman Miller, Lawrence Berkeley National Lab, Berkeley, California – GCM downscaling and hydrologic modeling.

Dr. Thomas Wigley, National Center for Atmospheric Research, Boulder, Colorado (At EPRI) – GCM model results.

September 2001

Stephen Verigin, Chief of the Division of Safety of Dams, DWR, Sacramento, California – Potential PMF changes.

Dr. Norman Miller, Lawrence Berkeley National Lab, Berkeley, California – Hydrologic modeling and review of draft report.

Dr. Nigel Quinn, Lawrence Berkeley National Lab, Berkeley, California – Hydrologic and water quality modeling.

Dr. Peter Gleick, Pacific Institute for Studies in Development, Environment, and Security, Oakland, California – Potential water resources research and review of draft report.

Dr. Jay Lund, U. C. Davis, Davis, California – Modeling climate change effects on water.

Dr. James Quinn, U. C. Davis, Davis, California – Review of draft report.

October 2001

Dr. Dan Cayan, Climate Research Division, Scripps Institution of Oceanography, U.C. San Diego, La Jolla, California – Climate research and review of draft report.

Dr. Michael Dettinger, Scripps/U.S.G.S. San Diego, at Scripps Institution of Oceanography, La Jolla, California – Climate research and review of draft report.

Dr. Noah Knowles, Climate Research Division, Scripps Institution of Oceanography, U.C. San Diego, La Jolla, California – climate research.

Appendix A
Current Status of Programs

This section outlines those efforts that most closely address the climate change issue and its impact on California.

Current Status: California

California Department of Water Resources

- The California Department of Water Resources has several studies underway. First is the California Water Plan Update, Bulletin 160–03, to be published in 2003. Second is the relicensing study for the Oroville power plants scheduled to be complete in 2005. Third would be proposed processing and Web dissemination of updated depth-duration-frequency rainfall data. Fourth, in cooperation with The Reclamation Board, participation in the Comprehensive Flood Study in the Sacramento and San Joaquin River basins, with the feasibility report scheduled for late 2002. The U.S. Army Corps of Engineers is the major partner in the Comprehensive Study.

California Energy Commission

- In cooperation with the Electric Power Research Institute, the Energy Commission has undertaken an ambitious program to evaluate the potential effects of climate change under different GCM scenarios in California. Items of study include hydrology, water resources, agriculture, energy and timber, and coastal resources.

University of California

- The California Applications Program *Improved Weather and Climate Forecast Information for California* is an ongoing program involving many researchers in the University of California and National Laboratory System who have been, and are doing, a wide variety of research on weather, weather forecasting, climate, and climate change. Much of the funding has come from NOAA. This program began in 1998 and is continuing. The program is administered by the Climate Research Division, Scripps Institution of Oceanography, in La Jolla (Dr. Daniel Cayan, director).

CALFED

- This is an ongoing cooperative Bay-Delta program of many federal and State agencies working on California water and environmental problems, with emphasis on the Delta. It is expected that the Program will invest $1 to 5 million per year for the next 10 years on climate change implications.

California Water Resources Research and Applications Center, Lawrence Berkeley National Laboratory, University of California.

- This group has been making a number of water resources studies and modeling studies, which include climate change. The most recent is a Climate Change Sensitivity Study of California Hydrology by Dr. Norman Miller and Kathy Bashford, assisted by Eric Strem of the NWS California-Nevada River Forecast Center in Sacramento, which is part of a California Energy Commission study administered by EPRI. The Center also receives funding from the U.S. Department of Energy.

U.S. Geological Survey

- The USGS has a number of important monitoring studies dealing with stream runoff, water quality, groundwater, coastal erosion, and climate change induced runoff changes on several California rivers, salinity in the San Francisco Bay, sedimentation in the Delta, Ventura County groundwater, and paleostudies of past climate. Many of these are continuing.

Hydrologic Research Center (San Diego) and Georgia Water Resources Institute (Atlanta)

- Konstantine and Aris Georgakakos have been investigating reservoir operations for some time. Recent studies have involved probabilistic forecasting, weather forecasting and climate change. They have proposed a five-year project, INFORM, for research development technology transfer and a demonstration program to users of the climate information for water resources management. Funds are being sought from the NOAA Office of Global Programs.

Current Status: Regional and National

U. S. Global Change Research Program

- The Global Change Research Program was established under the auspices of the President's National Science and Technology Council in 1989 and authorized by Congress in 1990. It is coordinated by a multi-agency Subcommittee on Global Change Research established by the Council's Committee on Environmental and Natural Resources. Research studies are conducted by nine federal agencies. The National Assessments for the nation and for a number of regions were funded by USGCRP. The Program seeks to provide a sound scientific understanding of the human and natural forces that influence the Earth's climate system—and thus provide a sound scientific basis for national and international decision making on global change issues. It seeks to observe, understand, predict, and assess the critical natural and human-induced dynamic states and trends of the Earth's global environmental system across a wide range of time and spatial scales.